IXO system studies and technology preparation

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ABSTRACT

The International X-ray Observatory (IXO) is a candidate mission in the ESA Space Science Programme Cosmic Visions 2015-2025. IXO is being studied as a joint mission with NASA and JAXA. The mission concept and X-ray telescope accommodation have both been studied in the ESA Concurrent Design Facility. Competitive industrial studies will now further investigate the issues raised, and will elaborate mission concepts.

In parallel the required technologies are being developed, with the main emphasis under ESA responsibility being focused on Silicon Pore Optics (SPO). A technology development plan has been made and its implementation is progressing well.

The paper presents a summary of the ESA system studies of IXO and provides an overview of the related ESA led technology preparation activities.

Keywords: IXO, High-energy Astrophysics, X-ray optics, Silicon Pore Optics

1. INTRODUCTION

The selection of mission candidates after the call for proposals for future science missions in the ESA Cosmic Visions 2015-2025 (CV1525) programme included XEUS as a large mission candidate [1,2]. The XEUS concept was later absorbed into the IXO mission candidate, which also considers and includes elements from studies done in the USA on the equivalent mission, Constellation-X X-ray observatory concept [3].

A major science driver for the design of IXO is the large required effective area of 3 m^2 at 1.25keV, combined with the required angular resolution of 5 arc seconds half energy width (HEW) below 7 keV. The implementation requires a novel optics technology to be developed and employed. In addition, a long focal length is needed, since this allows a greater photon-collecting capability at higher photon energies. A focal length of 20 metres has been selected for IXO as a balance between science requirements and engineering constraints. As no current launch vehicle is capable of accommodating a payload that is nearly 23 metres long, IXO will have a deployable structure to position the instrument module at the mirror focus after launch.

The IXO study includes the accommodation of six instruments:

- Wide-Field Imager – **WFI**
- Hard X-ray Imager – **HXI**
- X-ray Microcalorimeter Spectrometer – **XMS**
- High Time-Resolution Spectrometer – **HTRS**
- X-ray Polarimeter – **XPOL**
- X-ray Grating Spectrometer – **XGS**

Optics for EUV, X-Ray, and Gamma-Ray Astronomy IV, edited by Stephen L. O'Dell,
Giovanni Pareschi, Proc. of SPIE Vol. 7437, 743702 · © 2009 SPIE
CCC code: 0277-786X/09/$18 · doi: 10.1117/12.825967

Initial design studies have been performed in ESA's Concurrent Design Facility (CDF) at ESTEC and at NASA's Mission Design Laboratory at the Goddard Space Flight Center. We report here on the results of the ESA studies. Silicon Pore Optics (SPO) was chosen as the IXO baseline optics technology by ESA [4 -6], with a back-up optics technology being investigated in the USA and in Europe using slumped glass optics [7 – 11]. Independently of the technology used, the IXO optics is based on a Wolter-1 configuration, consisting of a doubly reflecting X-ray mirror system, comprising a parabolic and a hyperbolic segment working under grazing incidence.

2. IXO SYSTEM STUDIES BY ESA

IXO is a collaborative venture between NASA, ESA and JAXA and is under study for a launch around 2020. IXO will be launched on either an Ariane 5 ECA or Atlas V 551, with direct injection towards a large-amplitude halo orbit around the second Lagrange point (L2) of the Sun-Earth system. The main advantages of this orbit are a very stable thermal environment and minimal shadowing by the Earth or Moon. The journey to L2 will take just over 3½ months. The observational constraints are summarised in Figure 1.

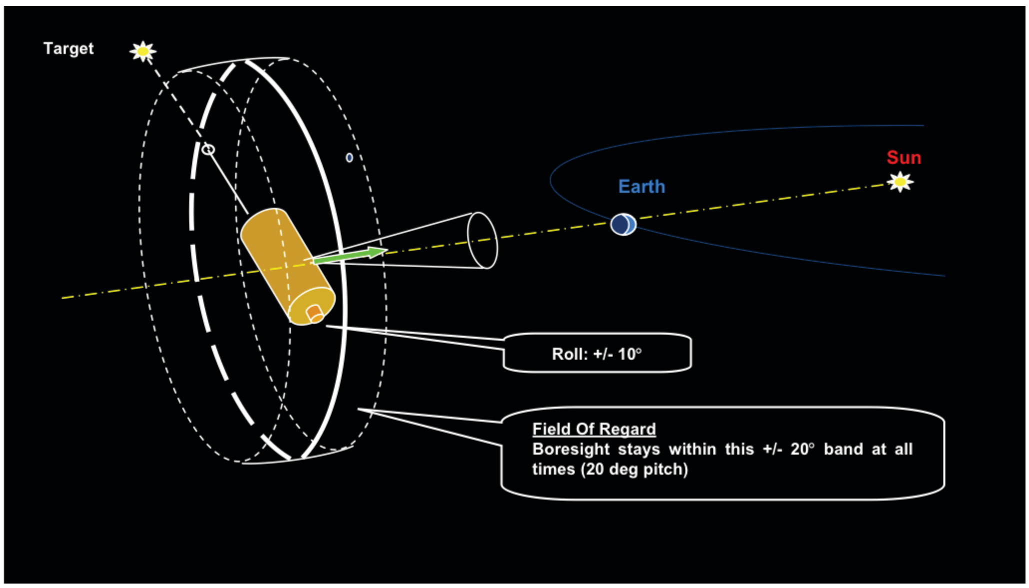


Figure 1: IXO field of regard: the spacecraft has been designed for a pitch angle of up to 20 degrees, allowing the telescope to access a 40-degree wide wedge of sky at all ecliptic latitudes.

IXO will have a launch mass of around 6600 kg and will be about 10 metres long and 4 metres in diameter in its launch configuration. The spacecraft will be about 23 metres long in its flight configuration (see Figure 2). The nominal mission lifetime is five years, with consumables sized for 10 years of operations.

The initial studies performed in the ESA CDF envisage a modular architecture, with the IXO spacecraft being made up of five major assemblies:

- **optics module** – mirror assembly with the associated straylight baffle assembly and deployable sunshield
- **fixed telescope structure** – a ~9.5 meters long, conical 3.9-2.7 meter diameter connection between the optics module and the service module
- **service module** – containing the satellite systems: power distribution, attitude control, propulsion, telecommunication and telemetry
- **deployable telescope structure** – required to position the instrument module from the stowed position to the mirror focal plane

- **instrument module** – carrying the six instruments, their associated electronics and thermal control systems, and a mechanism for positioning the selected instruments into the focal plane (the XGS CCD camera is positioned to the side of the focal plane and operates continuously).

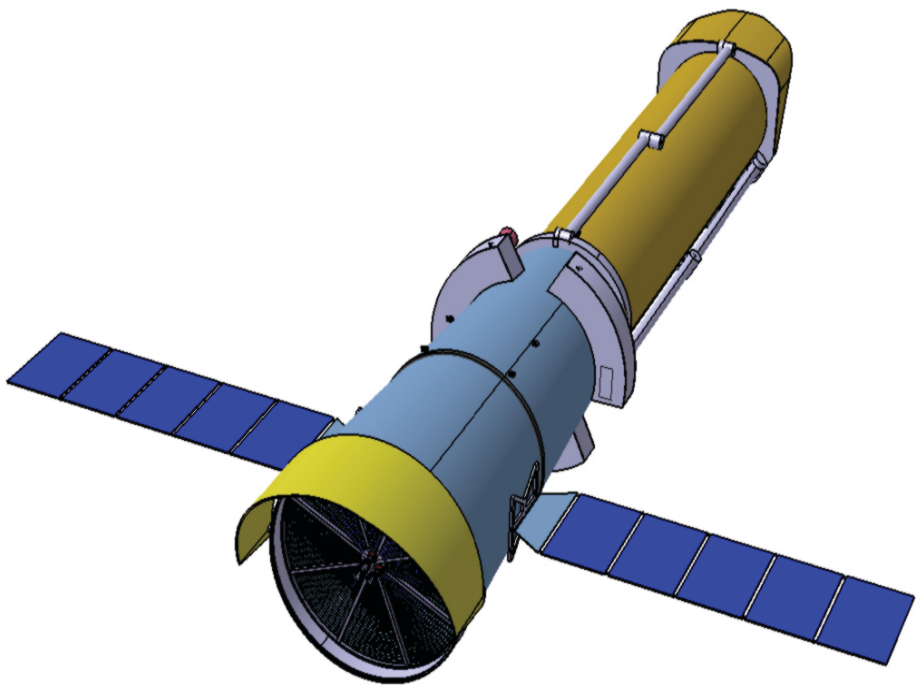


Figure 2: Schematic diagram of IXO in deployed configuration, as envisioned in the CDF studies.

The metering structure consists of a static segment and a deployment system consisting of three arms, not dissimilar to robotic arms as used e.g. on the International Space Station or on the Space Transportation System. The fixed telescope structure is a ~9.5 meters long, conical 3.9-2.7 meters diameter tube, which functions as a spacer to position the mirror assembly sufficiently far away from the service module. It is manufactured from composite fibre-reinforced plastic, with a wall thickness of 1~1.5 mm and 20~40 mm spacers. The materials and lay-up technique will be chosen to achieve a thermal expansion coefficient close to zero, maintaining the focal length of the telescope in the various thermal environments encountered during ground testing and on orbit.

The spacecraft's system module and sub-systems, including the solar arrays will be attached to the metering structure. The location of the Attitude and Orbit Control System (AOCS) sensors, the star trackers, must be carefully chosen so as so provide a reliable determination and monitoring of the telescope pointing, despite its size and flexibility.

To achieve the required distance between the optics and the focal plane instrument assembly, the current CDF baseline makes use of a deployment system consisting of three articulated arms. Figure 3 shows the deployment principle and sequence. Note the size of the person shown next to the IXO spacecraft. Three tubular arms, each with two sections and three joints, are stowed on the outside of the service module, extending over the fixed telescope structure. After launch, the arms are released and a motorised joint in the centre of each arm pushes the instrument module away from the service module.

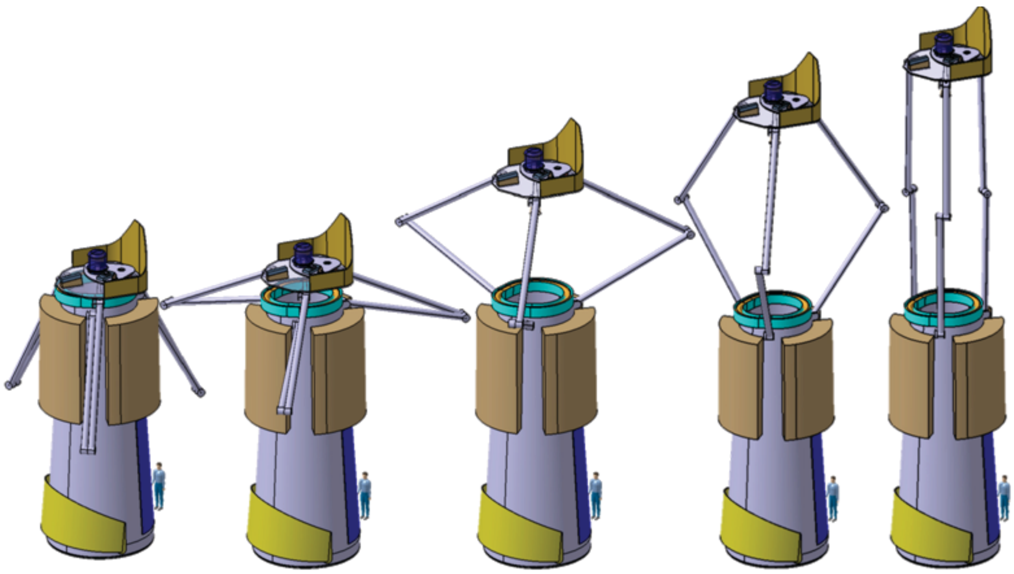


Figure 3: To achieve the required distance between the optics and the focal plane instruments, a deployment mechanism based on three articulated arms will be used. During launch, the three tubular arms, each with two sections and three joints, are stowed on the outside of the service module, and are secured to the fixed telescope structure by hold-down mechanisms. After launch, these are released and the arms are jointly deployed in a synchronised way.

A shroud is required between the instrument module and the service module, to prevent straylight from entering the instruments. The shroud will be positioned inside the deployed, articulated arms.

The shroud will consist of multi-layer insulation blankets, pleated like camera bellows. The pleats allow the shroud to be stored in a canister on the service module prior to deployment. To minimise light leaks caused by micrometeoroid penetrations, the shroud will be made up of two concentric MLI blankets separated by 100 mm, forming a 'Whipple shield'.

The optics accommodation poses critical demands on the mechanical and thermal environment provided to the optical modules (Figure 4). The optical bench is interfaced to the metering structure and the finally to the launcher, minimising the vibration and shock loads transmitted to the optics itself. In view of its large diameter, at 3.8 m, the optics payload is modular, with the current CDF baseline foreseeing eight petals. Each petal is populated by the X-ray Optical Modules (XOUs), which effectively perform like small thin lenses. The major alignments having small error budgets are performed during the assembly of the XOUs, whereas the alignment of the XOUs and petals can tolerate larger positional and angular tolerances.

The thermal environment of the optics is demanding. The temperature must be maintained to within narrow limits with gradients as low as achievable throughout all the mission phases. A Sun-shade and dedicated thermal baffles form part of the thermal control system for the telescope. A factor is the different environments faced by the optics: one side facing cold space, the other side the warm spacecraft. The thermal baffles facing towards space are therefore heated, and a considerable electrical power has to be provided to this sub-system.

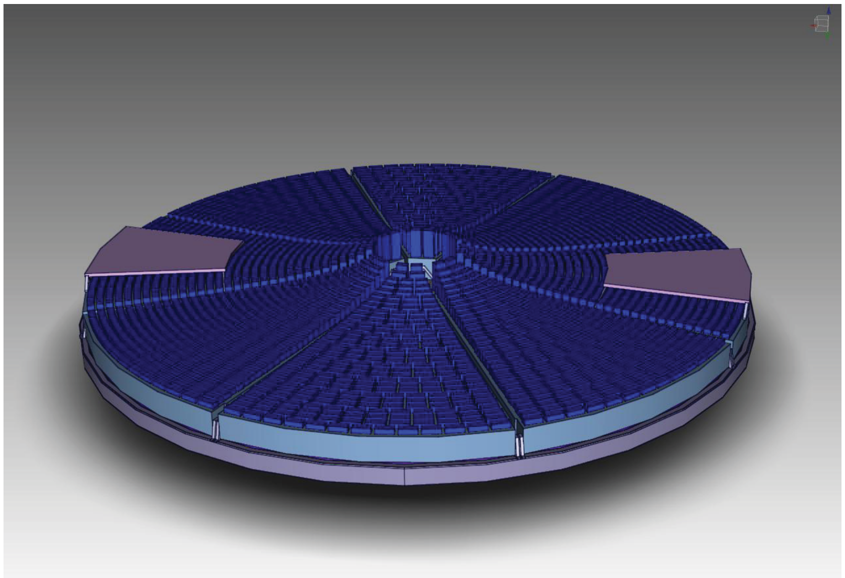


Figure 4: The telescope optics consists of optical modules mounted on an optical bench, itself accommodated in the fixed metering structure. The optics forms a significant mass element and is located at the bottom of the launch configuration of IXO. The launch loads including the separation shock must be properly mastered and the optics interfaces carefully designed. The thermal environment is also very critical, with a need to maintain the temperature within narrow limits and thermal gradients small throughout all the mission phases.

On the other end of the telescope structure the payload instruments are mounted on a rotation platform with focusing provisions, as illustrated in Figure 5. The four instruments / instrument combinations that operate at the focal point of the main beam will be mounted on a revolving platform with four stops, moved by redundant motors. The movable instruments will have a fine-focussing mechanism to allow them to compensate for changes in focus between ground testing and the flight environment. The required proximity electronics is also accommodated on the revolving platform and the remaining instrument electronics is accommodated on the fixed platform.

The XGS readout camera will have a focusing mechanism. The gratings will be located at the end of the fixed telescope structure nearest the service module, or in the service module itself, for the off-plane grating option, and on the mirror module for the transmission grating option.

All the instruments will be protected from incoming protons from the mirror module in the energy bands of interest by magnetic deflectors, positioned close to the detectors. In addition, there is a ~2 meter long conical baffle mounted on the fixed instrument platform, which shields the on-axis instruments from X-ray stray light.

The electronics on the movable instrument platform will be cooled by means of heat-pipe connections to a radiator. The instruments may have their own radiators looking to deep space. A fixed sunshield attached to the instrument module will keep the instruments in shadow at all times. The limitation of spacecraft roll (± 10 degrees) and pitch (± 20 degrees) with respect to the Sun line somewhat simplifies the task of stabilising the thermal environment for the instruments.

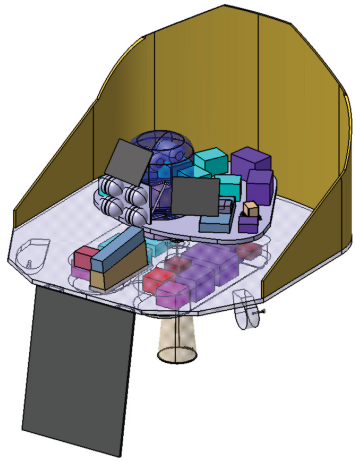


Figure 5: Focal plane instrument platform with associated rotational instrument exchange system, proximity electronics and baffling systems.

3. THE SILICON PORE OPTICS TECHNOLOGY AND ITS DEVELOPMENT PLAN

The IXO Optics Technology is the main enabling technology required to be developed for IXO. The development risk is being mitigated by the parallel development of two independent optics technologies, the Silicon Pore Optics (SPO), and the Slumped Glass Optics Technology. Other technology developments mainly regard the deployment mechanism, detector instrument coolers, detector instruments and their electronics.

A development plan has been established for the SPO technology, describing the roadmap leading to the Technology Readiness Level (TRL) demonstration as required for the adoption of the mission. This SPO TDP forms a part of the Cosmic Visions 2015-2025 ESA Science Programme technology preparation plan for the selected mission candidates, since IXO is one of three candidate missions selected for the first Large-Class mission, with an envisaged launch around 2020. At the time of down selection, currently foreseen for end of 2011, a TRL of 5-6 must be demonstrated.

The SPO technology has been funded by ESA since its conception, and has been developed successfully from a TRL1 in 2002 to the current TRL of 4. ESA has led and funded this programme, which was implemented in European industry. The ESA funding of SPO is continuing in pace with the evolution of the mission.

The ESA CV1525 L-class mission candidates in the assessment phase include IXO as a selected candidate. For each of the CV1525 mission candidates the funding is provided for both the system level industrial studies and the implementation of the technology preparation activities, again as industrial contracts. In the case of IXO, the main technology focus for ESA regards the IXO optics. The IXO optics based on SPO is regarded as potential European provision to the joint mission, where ESA is investing a substantial effort.

The core SPO technology developments are for the X-ray Optical Unit (XOU). The XOU is a complete Wolter-1 optical element, and includes the isostatic mounting. The SPO TDP targets the production of a prototype XOU, which is tested in the relevant environment and demonstrates the X-ray imaging performance.

The development progression of SPOs can be followed from their conception in 2001, to the 2007 demonstration of TRL 4, where a first laboratory breadboard of a mirror module demonstrated 17 arcsec HEW. ESA's development plan for the SPO has been prepared with the intention of meeting a schedule to demonstrate TRL 6 - prototype demonstration in the relevant environment - in 2011. An industrial team has been assembling and carrying out development activities in order to verify the technology applicability in the context of a space-based X-ray observatory such as IXO.

From its instigation, SPO development has pragmatically considered the technology's use in an industrialised context, addressing from a programmatic viewpoint the issues associated with mass production in a flight programme. Therefore the processes involved are, wherever possible, adapted from industrialised production procedures. The base material for the mirror plates is commercially available directly in a form suitable for use as an X-ray mirror. The manufacturing steps to produce X-ray optic modules have been developed using prototypes of production line equipment and automated, robotic testbeds that should facilitate the technology progression from a laboratory to an industrial, mass production environment.

The development plan at ESA addresses the steps necessary not only to demonstrate the SPO technology, but also to show that manufacturing; assembly, integration and test; periphery sub-systems; industrialisation and cost reduction of the optics will make a flight programme viable. The plan has been staged to prioritise development activities in a coherent way with system level studies, which will place requirements on the telescope components, and with the down selection of large missions at ESA.

The current status and the main targets of the SPO TDP are illustrated in Figure 6. The SPO employs standard semiconductor wafer technology processes to produce rectangular plates which have thin ribs on one side, and thin membranes between the ribs. The plates are bent into the required shape, and several plates are stacked to obtain a stiff pore structure, called a stack. The stacks are then mounted into a "tandem" structure creating an approximation to the Wolter I geometry. This unit is called an X-ray Optical Unit (XOU) or Mirror Module (MM), and is a complete X-ray imaging element, analogous to a thin optical lens. While the current technology developments are based on conical mirror figures, the production of SPO elements with a true Wolter-1 SPO is possible and will be undertaken in the near future. To form an X-ray mirror of the required dimensions, many XOUs are then assembled in an optical structure. For the telescope size required by IXO, the XOUs are assembled into petals, which in turn are integrated into the spacecraft optical bench.

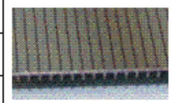
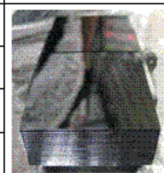
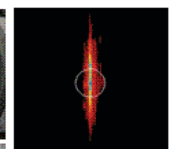
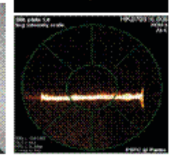
Steps	Done	TRL 2008		Next (2011)	TRL
Plate production	Industrial process	 	4	Reduce cost Different sizes	6
	Wedged, coated, non-conical				
	500 produced				
Stack production	Automated	 	4	Improve HEW	6
	Particle inspection, cleaning, bending, interferometry, stacking				
	200 produced				
Module production	Design to spec	 	3-4	Module ruggedising and Industrialisation and mass production	6
	Integration method to spec				
	Mounting method				
	4 produced				
Module validation & qualification	Synchrotron & beam testing in place	 	4	Environmental testing Focal plane testing	6
	Ruggedness assessment				
Petal production	Design to spec	 	4	Production of prototype	6
	1 produced				
Petal validation & qualification	First X-ray testing		4	Environmental testing Focal plane testing	6

Figure 6: The Technology Development plan (TDP) for the IXO optics. The core element of the optics is a Mirror Module (MM) or X-ray Optical Unit (XOU), which is formed by the parabola and hyperbola stacks solidly mounted together and equipped with an isostatic mount. The performance demonstration, proving the compatibility with the mission requirements in terms of angular resolution and effective area is the first priority. The ruggedizing of the XOU and the environmental testing builds on the design used for the performance demonstration, and refines it to become compatible with the vibration and thermal requirements of the mission. The petal breadboard activity can be started once the XOU is sufficiently developed, and the system design is adequately matured, providing the necessary details on the accommodation options. Last but certainly not least, the technical, tooling and programmatic aspects of mass-producing the XOUs are addressed in the fourth block. A similar approach is followed for the back-up optics technology, albeit at a lower level of resources.

6. CONCLUSION

The IXO mission is a candidate L-class mission in the ESA Cosmic Visions 2015-2025 science programme. ESA is undertaking system studies and implementing technology preparation activities in the current assessment phase. IXO is being jointly studied by ESA, NASA and JAXA, and reflects the high priority given to high energy astrophysics by the worldwide scientific community.

ESA internal system studies using the Concurrent Design Facility (CDF) have been completed, and ESA is now embarking on industrial system level studies. These will be performed by European industry consortia, in a parallel competitive way.

The key enabling technology for IXO is the X-ray optics technology. As a risk mitigation measure, two independent optics technologies have been identified, and both are being developed in parallel. The ESA baseline is the Silicon Pore Optics (SPO), with the Slumped Glass Optics technology (SGO) being the back-up and the NASA baseline.

ACKNOWLEDGEMENTS

We would like to acknowledge the work done by the CDF team in designing the IXO mission baseline, serving now as a starting point for the upcoming industrial system studies. We thank the IXO Sciecne Study Group for their guidance.

We also thank the industrial and institutional entities and the people involved in the technology preparation activities. Their work forms the basis, onto which the future science missions are built. Without their efforts the next generation high-energy astrophysics observatory, IXO, could not materialise.

REFERENCES

1. A. Parmar, G. Hasinger, & M. Turner, "XEUS - the X-ray Evolving Universe Spectroscopy Mission", Proc. 34th COSPAR Assembly, 2368, (2002).
2. G. Bignami et al., [Cosmic Vision, ESA BR-247], ESA Publications, Noordwijk, The Netherlands (2005).
3. J. Bookbinder et al., "The Constellation-X Observatory", Proc. SPIE 7011, 701102:1-15 (2008).
4. M. Beijersbergen et al., "Development of x-ray pore optics: novel high-resolution silicon millipore optics for XEUS and ultralow mass glass micropore optics for imaging and timing", Proc. SPIE 5539, 104-115 (2004).
5. M. Bavdaz et al., "Status of x-ray optics development for the XEUS mission", Proc. SPIE 5488, 829-836 (2004).
6. M. Bavdaz et al., "The XEUS x-ray telescope", Proc. SPIE 5900, 59000Z:1-9 (2005).
7. P. Friedrich et al., "Manufacturing of Wolter-I mirror segments with slumped glass", Proc. SPIE 6266, 62661G:1-8 (2006).
8. P. Friedrich et al., "Recent results on manufacturing of segmented x-ray mirrors with slumped glass", Proc. SPIE 5900, 59000W:1-8 (2005).
9. M. Ghigo et al., "The manufacturing of the XEUS x-ray glass segmented mirrors: status of the investigation and last results", Proc. SPIE 5168, 180-195 (2004).
10. R. Petre et al., "The Constellation-X Spectroscopy X-ray Telescope: recent technology development", Proc. SPIE 6266, 62661Q:1-9 (2006).
11. W. Zhang et al., "Development of lightweight x-ray mirrors for the Constellation-X mission", Proc. SPIE 5900, 59000V:1-11 (2005).